IMPACT OF CARDIAC MOTION ON DEFORMATION ESTIMATION OF STRUCTURES IN INTRAVASCULAR ULTRASOUND

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Abstract: Intravascular ultrasound (IVUS) is an imaging modality that enables the physician to visualize structures of coronaries from inside. However, since it is performed on living patients, the heart motion generates artifacts that make structure tracking more difficult for both humans and computers. This study is a quantitative analysis of the impact of heart motion on structures deformation estimation using the classical algorithm of Lucas-Kanade for Optical Flow (OF). This work included a 3D IVUS simulation with artifacts caused by catheter longitudinal displacement and blood vessel deformation due to blood pressure variation. Then, OF was applied to the IVUS images sequence and to a subset of the sequence that considers one phase of the cardiac cycle. The points located at the border of structures presented good movement estimation. In the other hand, for the point located in a homogeneous region, the error of the movement estimation with heart motion was four times greater than the related movement estimation considering only one phase.
Keywords: IVUS, optical flow, heart motion.

Introduction

Cardiovascular diseases present an important impact on mortality, morbidity, ambulatory and hospitalizations expenses [1] in Brazil. The most common diseases are myocardial infarction, angina (chest pain), atherosclerosis and cerebral vascular accident (CVA). In 2003, 11% of inpatient hospitalizations on SUS (Unified Health System - Brazil) were caused by problems in the cardiovascular system. In the same year, those diseases were responsible for 19.46% of hospitalizations expenses on SUS. Furthermore, cardiovascular diseases are the main causes of death in Brazil, about 20% [1]. The situation is not different in developed countries, e.g. Portugal and United States of America (USA). In USA, American Heart Association [2] estimated that around 64,400,000 people present at least one cardiovascular pathology. In Portugal, cardiovascular diseases are responsible for approximately 40% of death [3]. Considering those facts, several studies are being developed in order to enhance medical techniques, prevent cardiovascular diseases and improve outcomes in therapies and interventions.

Intravascular ultrasound (IVUS) is an examination that provides real-time visualization of the interior of a blood vessel through catheterism. Its main target is the visualization of the coronaries, arteries that irrigate the heart. The catheter has one or more transducers on its tip, which are responsible for emitting and receiving IVUS beams. Usually, 256 signals are equiangularly distributed in the plane that is perpendicular to the catheter longitudinal axis. During IVUS procedure, the catheter, which was previously inserted into the patient, provides images of the blood vessel while it is pulled back. The pullback is performed by an external motor that retracts the catheter at a constant speed - typically 0.5 or 1.0 mm/s. So the images are acquired from the distal to the proximal part of the vessel in relation to the insertion position. IVUS images are slices, cross-sectional to the catheter longitudinal axis, which provide information about the inner portion of the vessel, allowing the visualization and quantification not only of the vessel lumen, but also of the arterial wall and its structures, such as atherosclerotic plaque Therefore, IVUS is an important instrument to assess the severity of a cardiovascular disease.

The estimation of the structures deformation in a sequence of IVUS images is important to characterize lesions and analyze the risk that it offers to the patient. Elastic lesions are associated with a lipid pool covered by a thin cap, which may rupture and cause cardiovascular accident.

Since the IVUS images are obtained from living patients, the heart contractions displaces the catheter inside the blood vessel, making movement estimation of the imaged structures more difficult for both humans and computers. In this work, we quantify the impact of the cardiac contractions in movement estimation utilizing numeric simulation.

Methods

There are numerous computational procedures involving ultrasound images, such as filtering [4], segmentation [5] and elastography [6]. Unfortunately, the validation of those techniques using clinical images is hindered by the lack of gold-standard parameters. An alternative solution is to simulate the ultrasound images considering dynamic deformation, pullback path and heart movement. With the numeric simulation, we can divide the cardiac cycle into phases, which enables the acquisition of data from the heart in specific positions.

In this study, we created a 3D mesh with finite elements method to simulate the blood vessel and its deformation. Then, linear isomorphism [7] was applied to estimate the IVUS scatterer displacement according to the mesh deformation. Next, the catheter position inside the coronary was determined using equilibrium of forces [8]. Then, IVUS was simulated utilizing Field II [9]. Finally, structure motion estimation was performed with Optical Flow [10].

Artery Simulation – A volumetric mesh was created to simulate an artery with lesions. Then, perpendicular forces were applied to the nodes in the lumen surface in order to simulate the internal blood pressure variation due to cardiac contraction (Figure 1).

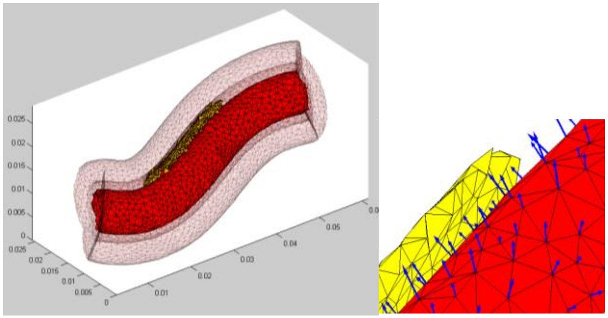

Figure 1: Left, artery mesh with its structures (lumen in red, artery wall in light red and lesions in yellow). Right, forces, in blue arrows, applied at the nodes in the lumen forces.

The ultrasound scatterers are initially distributed in the phantom. Then, after the blood vessel deformation, the scatterer displacement is determined through linear isomorphism [7], which is responsible to determine the position of all the scatterers inside a tetrahedron after its deformation (Figure 2).

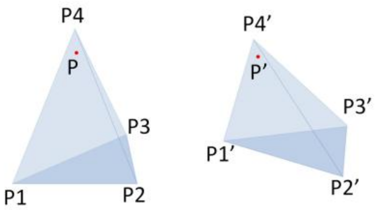

Figure 2: Left, scatterer (in red) in its initial position, P, inside the tetrahedron. Right, scatterer position, P', after the deformation of the tetrahedron.

Guidewire Path Determination – The guidewire deformation is performed by forces that are applied iteratively at the vertices [8] (Figure 3a). The forces may be divided into three groups according to their nature: a) Longitudinal forces, f^L, which account for maintaining the guidewire length (Figure 3b); b) Angular forces, f^C, that are responsible for unbending the guidewire, leading to the minimum energy position (Figure 3c); and c) External forces, f^E, which are performed by the blood vessel that constrains the guidewire to its interior (Figure 3d).

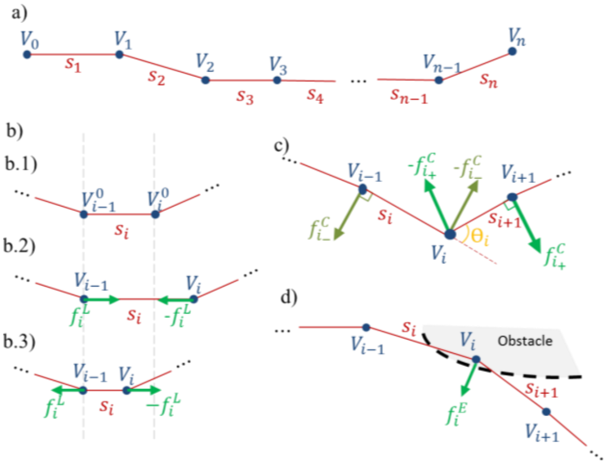

Figure 3: a) Representation of the numeric guidewire model. b.1) Illustration of s_i with its original length and its two consecutive vertices V_{i-1} and V_i , b.2) case in which the length of s_i is greater than the original length and f_i^L is applied in V_i towards V_{i-1} and vice versa b.3) case in which the length of s_i is smaller than the original length and f_i^L is applied in V_i away from V_{i-1} and vice versa. The vertical dashed lines indicate V_i and V_{i-1} original position. c) Illustration of f^C, which forces the alignment of V_{i-1}, V_i and V_{i+1}. d) Illustration of f^E, external force that pushes the node away from the obstacle and is responsible to keep the catheter inside the blood vessel wall.

Pullback Simulation – In order to simulate the catheter guided by a plastic sheath (guidewire), only one computed path is considered for each cardiac phase. The catheter tip will travel through the sheath path from distal to proximal portion as illustrated in the sequence of Figure4a-d.

A cubic spline is computed in order to obtain greater resolution between two consecutive points of the path. Each point of the spline has an associated length value, which is the distance to the proximal point through the curve.

This method provides the catheter path that is formed by a sequence of nodes. The catheter tip is located at the most distal node of the path and its direction is calculated as the difference between the position of the last node and the position of the penultimate node.

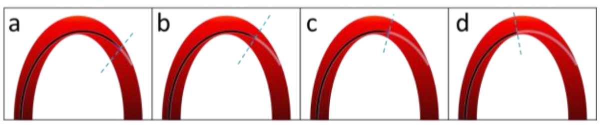

Figure 4: Pullback sequence. The blue dashed line depicts the plane that is perpendicular to the catheter tip, hence, the cross-section that is being imaged.

Data acquisition and IVUS simulation – For each IVUS image, considering the catheter tip position and direction, 256 IVUS beams were emitted from the catheter tip, equiangularly distributed in the plane perpendicular to its longitudinal axis. The emission, interaction with the tissue and reception of the ultrasound was performed by Field II [9]. Finally, the resulting RF data were utilized to build a sequence of B-mode images with 512x512 pixels.

Structures movement estimations – In this work, the movement estimation was performed using Optical Flow as proposed by Lucas-Kanade [10].

Results

The simulation of the sequence of IVUS images was performed with the parameters shown in Table 1.

Table 1: Parameter used in this simulation.

Parameter	Value
Ultrasound Frequency	40 MHz
Number of transducers	1
Number of US beams per image	256
Pullback Speed	0.5 mm/s
Heart Rate	90 bpm
Frame Rate	15 fps
Frames per Cardiac Cycle	10
Imaged length	5 mm
Total number of frames	151 frames

In order to simulate the heart dynamics, the cardiac cycle was divided into 10 phases. Each phase has a different incremental pressure that is related to the variation of blood pressure and may deform the blood vessel from inside. The longitudinal displacement due to cardiac motion is also being considered. According to [11], in a cardiac cycle the catheter moves 1.5±0.8mm longitudinally inside the blood vessel. This phenomenon was simulated by changing the catheter (and sheath) penetration length. The pressure increase and longitudinal displacement for each cardiac phase are shown in Table 2. A total of 10 s of continuous IVUS was simulated, comprising 5 mm of pullback, 151 frames, and 16 frames of phase 1.

Table 2: Catheter longitudinal displacement (LD) in mm and pressure increase (PI) in mmHg for each phase.

Phase	PI	LD	Phase	PI	LD
1	0	0	6	30	-1.2
2	20	-0.7	7	25	-0.9
3	30	-1.3	8	20	-0.6
4	40	-1.5	9	12	-0.3
5	35	-1.4	10	6	-0.1

In order to compare the impact of cardiac motion on structure tracking, optical flow was applied to two different sets of images: 1) The whole sequence of IVUS images, considering the 10 phases, and 2) The set of images that belong to phase 1. Then, both results were compared to the gold-standard. Since images that belong to a same cardiac phase (set 2) will not be affected by heart movement, it is expected that the error will be less than for the set 1. However, pullback movement will affect both sets, more severely on set 2.

Figure 5 illustrates the first image from the sequence of IVUS images with the 3 points used in the structure tracking.

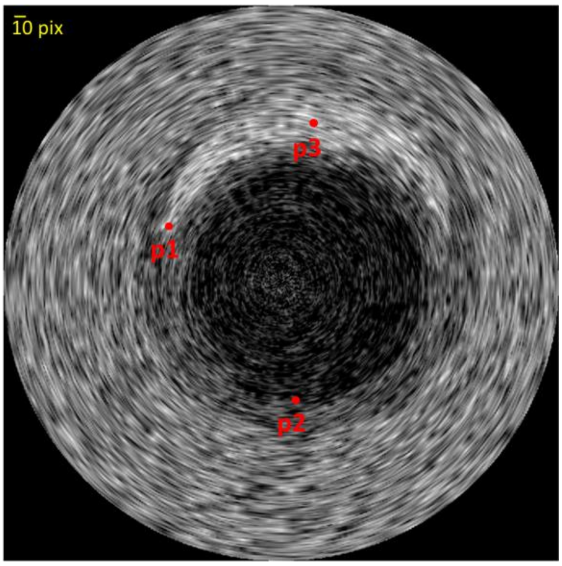

Figure 5: Simulated IVUS image and the points that were tracked: p1 at the left border of the lesion, p2 at the inferior limit of the lumen. And p3 at the center of the lesion. The yellow horizontal line at the upper left shows length of 10 pixels.

Figure 6 shows the movement estimation error in pixels of the 16 images from phase 1 and the first 16 images from the whole IVUS sequence (Figure 6a-c). It also presents the error along the complete IVUS sequence with the error of images from phase 1 in their related position (Figure 6d-f). All error results are shown in pixels. The yellow horizontal line at the upper left of Figure 5 shows magnitude of a 10-pixel error.

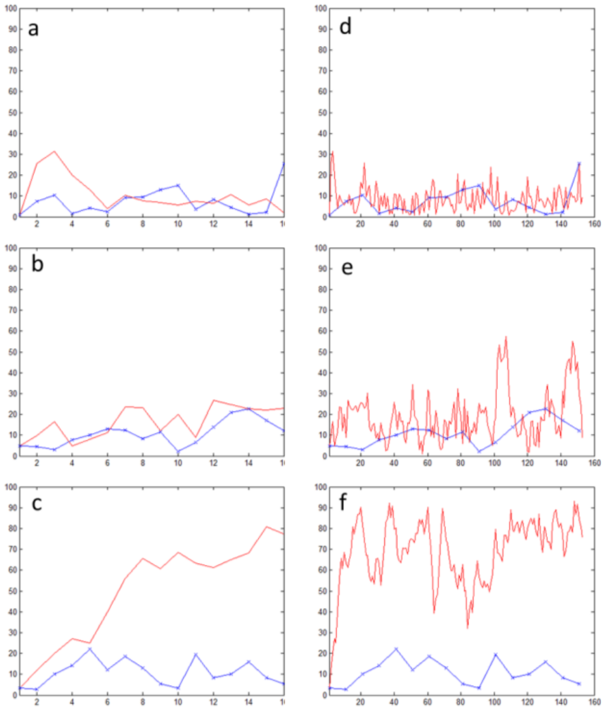

Figure 6: a, b and c shows the movement estimation error (in pixels) of the 16 first IVUS images of the sequence (red) and the 16 images from phase 1 (blue) considering p1, p2 and p3, respectively. d, e and f illustrate the movement estimation error of the whole IVUS images of the sequence (red) and the images from phase 1 (blue) considering p1, p2 and p3, respectively.

Discussion and Conclusions

From Figure 6, it is possible to see that, in the case of the points located at the lumen and lesion borders, the movement estimation errors with the heart motion were close to the errors considering only one phase of the cardiac cycle. However, the point located at the middle of the lesion structure has poor movement estimation in the presence of cardiac motion, while the movement estimation considering the same phase presented good results. Therefore, heart motion is more likely to hinder the tracking of structures in homogeneous regions. This analysis shows the importance of IVUS synchronization with EKG for quantitative purposes and suggests that tracking techniques provides more reliable results with frames separated according to cardiac phases.

This study considered the catheter longitudinal displacement and blood vessel deformation due to variation on internal pressure, which reproduces the dynamic effects of clinical IVUS acquisition. Future work may include different examples as well other IVUS artifacts, such as catheter twist, which causes image rotation.

Acknowledgments

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References

[1] C.G. Costa, Endemias Cardiovasculares no Brasil. . A.C. Lopes, Tratado da Clínica Médica. 1st Ed. São Paulo: Editora Rocca; 2006. Pp. 402-406.

[2]Available:http://www.americanheart.org/downloadable/heart/1140534985281Statsupdate06book.pdf . Last access: 14/5/2014.

[3] Ministério da Saúde de Portugal. Portal da Saúde – Portugal – 2006. Available on: http://www.portaldasaude.pt/portal/conteudos/enciclopedia+da+saude/doencas/doencas+do+aparelho+circulatorio/doencascardiovasculares.htm . Last Access: 14/1/2013.

[4] F.M. Cardoso, M.M.S. Matsumoto and S.S. Furuie, "Edge-Preserving Speckle Texture Removal by Interference-Based Speckle Filtering Followed by Anisotropic Diffusion", Ultrasound In Medicine And Biology; v. 38, n. 8 AUG 2012., 2014);

[5] S. Lobregt, M.A. Viergever, "A Discrete Dynamic Contour Model.", IEEE Transactions on Medical Imaging, Vol. 14, No. 1. (1995), pp. 12-24

[6] R. L. Maurice, J. Ohayon, G. Finet, G. Cloutier, "Adapting the Lagrangian speckle model for endo vascular elastography.", Journal of Acoustic Society of America, vol.116, no.2, pp. 1276-1286, Ago 2004

[7] F.M. Cardoso, M.C. Moraes, S.S. Furuie, "Realistic IVUS image generation in different intraluminal pressures.", Ultrasound in Medicine and Biology, vol. 38, No. 12, pp. 2104-2119, Aug. 2012.

[8] F.M. Cardoso and S.S. Furuie, "Guidewire path simulation using equilibrium of forces ", Proc. SPIE 9033, Medical Imaging 2014: Physics of Medical Imaging, 90334U (March 19, 2014);

[9] J. A. Jensen, "Field: A program for simulating ultrasound systems," Med Biol Eng Comput, Supplement 1, Part 1 34, pp. 351-353, 1996.

[10] B. Lucas and T. Kanade, "An iterative image registration technique with an application to stereo vision," Darpa Image Understand Workshop, 1981.

[11] A. Arbab-Zadeh, A. deMaria, W. Penny, R.Russo, B. Kimura, V. Bhargava, "Axial movement of the intravascular ultrasound probe during the cardiac cycle: Implications for three-dimensional reconstruction and measurements of coronary dimensions.", American Heart Journal Nov 1999;138(5):865-72